TIME COURSE OF ADAPTATION TO A SPLIT-CRANK ERGOMETER

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TIME COURSE OF ADAPTATION TO A SPLIT-CRANK ERGOMETER

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SUMMARY

Interlimb neural coupling has previously been studied to determine how both able-bodied and pathological populations move. Unfortunately, studying locomotor adaptation can be a difficult task. Often, split-belt treadmills are used, which present confounding variables, such as interferences from the head, arms, and trunk (Ting et al., 2000; Raasch & Zajac, 1999). Split-crank ergometers are a novel device that can be used in place of treadmills for both rehabilitation and research. In these ergometers, the bracket connecting the two cranks has been removed, allowing for the isolation of the mechanically decoupled (neural) locomotor coordination of the individual legs. While these ergometers have been successfully used in research and rehabilitation, little is known about how subjects adapt to the novel cycling task. In order to capitalize on the potential these ergometers provide, it is important to understand the time course of adaptation to the ergometer as well as the mechanisms of adaptation. This information will provide insight into how locomotor adaptation occurs and will aid in determining training regimens for cycling on this device.

Analyzing the time course of adaptation includes determining if adaptation occurs within and across cycling trials and if learning occurs on a succeeding day. It has previously been shown that able-bodied individuals can adapt to locomotor tasks by adjusting motor commands to compensate for unexpected outcomes. This causes the motor error to decrease until it reaches a persistent residual error (Smith, Ghazizadeh, & Shadmehr, 2006; Krakauer, Pine, Ghilardi, & Ghez, 2000; Thoroughman & Shadmehr, 2000). To

determine if learning has occurred on a subsequent day, savings and consolidation can be measured. Savings, a property of memory where prior learning increases the rate of improvement, has previously been shown in locomotor tasks (Smith et al., 2006; Canning, Ada, & O'Dwyer, 1999; Davis & Hull, 1981). Consolidation, the stabilization and enhancement of motor memories that occur during sleep, has been shown to occur within 24 hours during motor learning (Walker & Stickgold, 2004)

Research focused on the adaptation that occured over 2 days of participation in a novel cycling task. Determining the residual error of a split-crank cycling task will increase understanding of this adaptation time course. By seeing how long it takes for subjects to reach this residual error during their initial adaptation phase, it can be determine how long they will need to train on their first day of the adaptation task. In addition, it was determined if consolidation and savings occurred on day 2, which will provide insight into how long subjects must train on a subsequent day to reach the same level of adaptation. To determine the time course and mechanisms of adaptation, subjects were asked to cycle on a split-crank ergometer on 2 successive days. Kinetic and kinematic data were collected, and adaptation on day 1 and consolidation and savings on day 2 were measured. Subjects were able to adapt to the ergometer within and across trials on day 1 and day 2. Our results suggest that subjects can reach a baseline crank offset of less than 20° after just 10 minutes of cycling on day 1 and can reach this same baseline crank offset after 3 minutes of cycling on a subsequent day. Though there was a noticeable improvement on day 2, subjects did not exhibit consolidation or savings. There were no significant changes in resultant force or ankle angle; however, subjects significantly varied their resultant forces as they were adapting

CHAPTER 1

INTRODUCTION

Interlimb neural coupling is a phenomenon in humans about which little is known. Recently, research using a split-crank ergometer, which removes the effects of mechanical coupling, has been used to learn more about this interlimb neural coupling (Ting, Kautz, Brown, & Zajac, 2000; Alibiglou & Brown, 2011; Ting, Raasch, Brown, Kautz, & Zajac, 1998). In addition, research using these novel ergometers has been used to study the effects adapting to a locomotor task has on people with motor disabilities, such as stroke victims suffering from hemiparesis. While we are gaining more of an understanding of this neural coupling, we know little about the time course needed to adapt to this novel cycling task (Ting et al., 2000; Alibiglou & Brown, 2011; Ting et al., 1998). By determining the time course for this adaptation task, we will be better able to create a training regimen for learning to cycle on these ergometers. In addition, analyzing the kinetic and kinematic changes that occur during the adaptation task will allow us to better understand how this adaptation occurs. Only once we understand this time course can we effectively utilize the potential split-crank ergometers have in the field of research.

1.1 ADAPTATION

Motor adaptation is a learning phenomenon in which learning is influenced by sensory prediction errors. It is a feed-forward mechanism, meaning that motor commands are sent through the nervous system in anticipation of how the body should react with the external environment. Adapting to a locomotor task involves error-based adaptation. During error-based adaptation, the brain will adjust motor commands if a previous motor command resulted in an unexpected or undesirable outcome. The brain continues to adjust its motor commands during adaptation to compensate for the unexpected outcome, and the motor error decreases until it flat lines at the persistent residual error (Smith, Ghazizadeh, & Shadmehr, 2006; Krakauer, Pine, Ghilardi, & Ghez, 2000; Thoroughman & Shadmehr, 2000).

Motor adaptation studies are often conducted through visuomotor movements, reaching movements in a force field, and on split-belt treadmills. Unfortunately, adaptation to visuomotor movements and reaching tasks do not necessarily reflect the adaptation that occurs during locomotor tasks. Locomotion is a rhythmic movement that involves central pattern generators in the spinal cord. Reaching tasks, on the other hand, are discrete movements that depend on cortical substrates (Mawase, et al., 2014). Like with reaching tasks, adaptation to visuomotor movements cannot be generalized to explain locomotor adaptation (Krakauer, Ghez, & Ghilardi, 2005). To accurately study the adaptation to locomotor movements, one must study locomotor movements themselves.

1.1.1 Split-crank ergometers

Understanding the underlying causes of motor adaptation are important in providing a baseline of knowledge that allows us to predict the motor output we would expect to see in all kinds of motor adaptation. In addition, the applications of this knowledge will aid rehabilitation practices and the design of bio-inspired robotics. Researching human locomotor activities on a treadmill is difficult due to many confounding variables, such as balance and the interference from the head, arms, and trunk (Ting et al., 2000; Raasch & Zajac, 1999). Therefore, split-crank ergometers have been used to study motor adaptation and the underlying mechanisms of neural interlimb coupling. Ergometers minimize these variables and central and peripheral influences that cannot be isolated during walking or running (Ting et al., 2000; Raasch & Zajac, 1999). They can be used instead of treadmills to study adaptation of locomotor movements, because cycling still provides the rhythmic movement and appropriate phase relationship of the legs needed to study locomotion (Ting et al., 2000; Raasch & Zajac, 1999).

1.1.2 Motor disability

It has been found that abnormal motor output of the paretic limb can adversely affect motor movement of both lower limbs since they are neurologically coupled. In a 2011 cycling study on stroke survivors, Alibiglou & Brown showed that the sensorimotor state of the non-paretic limb influences the paretic limb due to neural interlimb coupling (Alibiglou & Brown, 2011). In addition, it has been shown that even in intact individuals, the extensor force generation of the contralateral leg influences the flexion-phase motor output in the ipsilateral leg during cycling tasks (Ting et al., 2000; Ting et al., 1998). People suffering from motor disabilities, such as stroke survivors experiencing hemiparesis, may experience abnormal motor movement and muscle activation patterns (Ting et al., 2000; Alibiglou & Brown, 2011; Ting et al., 1998; Liang & Brown, 2013; Cruz & Dhaher, 2008; Canning et al., 1999). For example, paretic limbs have been shown to produce abnormal muscle force, abnormal lower limb torque coupling, and muscle weakness (Liang & Brown, 2013; Cruz & Dhaher, 2008; Canning et al., 1999). It has been suggested that rehabilitation for muscle weakness focus on increasing the speed of muscle contractions and increasing the muscle force levels, both of which split-crank ergometers can be designed to do (Canning et al., 1999). Split-crank ergometers provide an addition benefit to regular ergometers, because users can receive feedback on the motor output of individual legs without the interference of mechanical coupling (Ting et al., 2000).

By using a split-crank ergometer, those with motor disabilities can focus on improving their motor output, which will improve their ambulation and increase their independence. In addition, studying the adaptation of intact individuals to a non-perturbed bilateral split-crank cycling task will allow us to learn more about how those suffering from hemiparesis, or other motor disabilities, would adapt to split-crank cycling. Alibiglou & Brown showed that cortical or subcortical stroke does not affect feedback adaptive strategies and that unilateral hemispheric stroke does not affect adaptation in either the paretic or non-paretic limb (2011). In addition, it has been found that the motor cortex does not significantly affect initial motor adaptation (Richardson et al., 2006). Thus we can conclude that those suffering from motor disabilities caused by damage to the motor cortex are likely to adapt similarly as intact individuals.

1.2 MOTOR LEARNING TIME COURSE

Split-crank ergometers have great potential to be extremely beneficial in the field of research and in the application of physical rehabilitation, but little is known about the time course of adapting to this motor task. In order to fully utilize the benefit ergometers provide, we must first understand the time course of adaptation to this novel cycling task and determine when, if at all, a residual error is reached. Research shows that a persistent residual error occurs during adaptation tasks, signifying incomplete compensation (Vaswani et al., 2015). State space learning models explain this residual error as the balance between error-based learning and a reversion to baseline (Vaswani et al., 2015). Savings, a property of memory characterized by a faster rate of relearning, and consolidation, the stabilization and enhancement of motor memory, have been shown to occur in locomotor tasks (Smith et al., 2006; Walker & Stickgold, 2004). By analyzing how long it takes subjects to reach a residual error, we can determine the time course for adaptation to this locomotor task. In addition, determining if consolidation and savings occur will determine if there are any changes to the time course of adaptation on a subsequent day as well as if learning occurs.

1.2.1 State space models

State space models have been widely used to predict motor outputs during adaptation tasks and to explain phenomena found during adaptation. For example, they have been used to explain why a residual error occurs during adaptation, even after several trials (Smith et al., 2006; Kording, Tenenbaum, & Shadmehr, 2007). State-space models explain this residual error as the balance between error-based learning seen within the trial and a reversion to baseline seen between trials (Vaswani et al., 2015). They are fairly accurate in their predictions during error-based adaptation. During error-based adaptation, the brain will adjust motor commands if a previous motor command resulted in an unexpected or undesirable outcome.

Over time, different state-space models have been created. The most basic and widely used state space model is the single-state, single time constant model. This model is good at assessing patterns of generalization and predicting responses to novel and random perturbations (Smith et al., 2006; Scheidt, Dingwell, & Mussa-Ivaldi, 2001). Unfortunately, this model predicts only a single time constant, though it has been shown that time constants of adaptation can increase or decrease from a baseline (Smith et al., 2006; Brashers-Krug, Shadmehr, & Bizzi, 1996). In addition, the single-state model does not account for adaptation paradigms, such as rapid de-adaptation (Smith et al., 2006; Shadmehr, Brandt, & Corkin, 1998); savings (Smith et al., 2006); anterograde interference, where initial motor adaptation leads to a worse initial performance and a shorter time constant during the opposite motor adaptation (Smith et al., 2006; Shadmehr et al., 1998); rapid downscaling, where the unlearning of a motor adaptation is faster than the initial learning it (Smith et al., 2006; Shadmehr et al., 1998); and spontaneous recovery (Smith et al.,2006).

1.2.2 Consolidation and savings

Consolidation of motor learning is the stabilization and enhancement of motor memories that occurs during sleep (Walker & Stickgold, 2004). In motor learning, consolidation has been shown to occur within 24 hours as indicated by lower error magnitudes (Walker & Stickgold, 2004). Savings is a property of memory that is characterized by a faster rate of relearning than the rate of initial learning, even after a period of washout (Canning et al., 1999; Davis & Hull, 1981). Savings has been studied over a period of multiple days in saccade tasks (Robinson, Soetedjo, & Noto, 2006; Kojima, Iwamoto, & Yoshida, 2004) and has been studied within the same day in a locomotor task (Mawase et al., 2014). To our knowledge, it is not yet known if savings of a locomotor adaptation task will be present on a subsequent day.

1.3 PURPOSE

The purpose of this research is to analyze the time course for learning how to pedal the split-crank ergometer so that we can gain more insight into how able-bodied individuals adapt to the novel cycling task and if they are able to show consolidation and savings on the second day of cycling. Analyzing the changes in kinematics and kinetics that occur during the adaptation task will aid in the understanding of how adaptation occurs during this time course. It will be additionally beneficial, because it will give researchers a basis to compare kinetic and kinematic data to. Once we know what kinematics and kinetics occur during split-crank adaptation tasks at the residual error, we will be able to compare them to changes that occur during perturbations of split-crank cycling.

Subjects cycled for 5x5-minute trials on day 1 of the study and returned on the second day to cycle for 5 minutes while performing the same cycling task as they did on day 1. We hypothesized that subjects would show adaptation on day 1 of the study. Specifically, subjects would show adaptation within and across trials, as it has been previously found that subjects adapt to novel motor movements within the first few minutes of a task due to the updating of learning modules (Smith et al., 2006; Reisman, et al., 2007). In a study by Smith et al., it was found that learning occurs through fast and slow learning modules, and that the two are not mutually exclusive (2006). It has also been found that consolidation of novel motor movements can occur within a few hours (Smith et al., 2006) and savings can occur within the same day (Mawase et al., 2014). Therefore, we further hypothesized that consolidation and savings would occur on day 2 because adaptation on day 1 indicates that fast learning occurred, which allows us to conclude that slow learning will be evident on day 2.

CHAPTER 2

MATERIALS AND METHODS

2.1 SUBJECTS

Data were collected on 7 able-bodied subjects (6 males, 1 female; age: 27.68 ± 7.74 years; mass: 82.24 ± 9.46 kg; leg length: 92.8 ± 3.07 cm) who gave written informed consent to participate in the Georgia Institute of Technology IRB approved protocol. Subjects had some cycling experience prior to participation in the study and did not have current or previous major musculoskeletal or neuromuscular injuries. Potential subjects were excluded from the study if they were pregnant, diabetic, sedentary, or had a cardiovascular or neurological disorder.

2.2 EXPERIMENTAL PROTOCOL

Subjects pedaled on a custom split-crank cycling ergometer (Fig. 1) with custom instrumented pedals (Broker & Gregor, 1990) on which the cranks have been mechanically decoupled. The decoupled cranks were attached to constant-force springs to supply a resistive torque during extension and assistive torque during flexion to simulate normal coupled, bilateral pedaling. Subjects wore a standard set of cycling shoes, which attached to clip-in pedals to ensure that contact between the feet and pedals was maintained at all times.

Data collection took place over 2 days. During both days, subjects were instructed to maintain a constant cadence of 60 rpm and a constant pedal phasing of a 180° offset to the best of their abilities. A metronome was used to assist subjects with their pedal

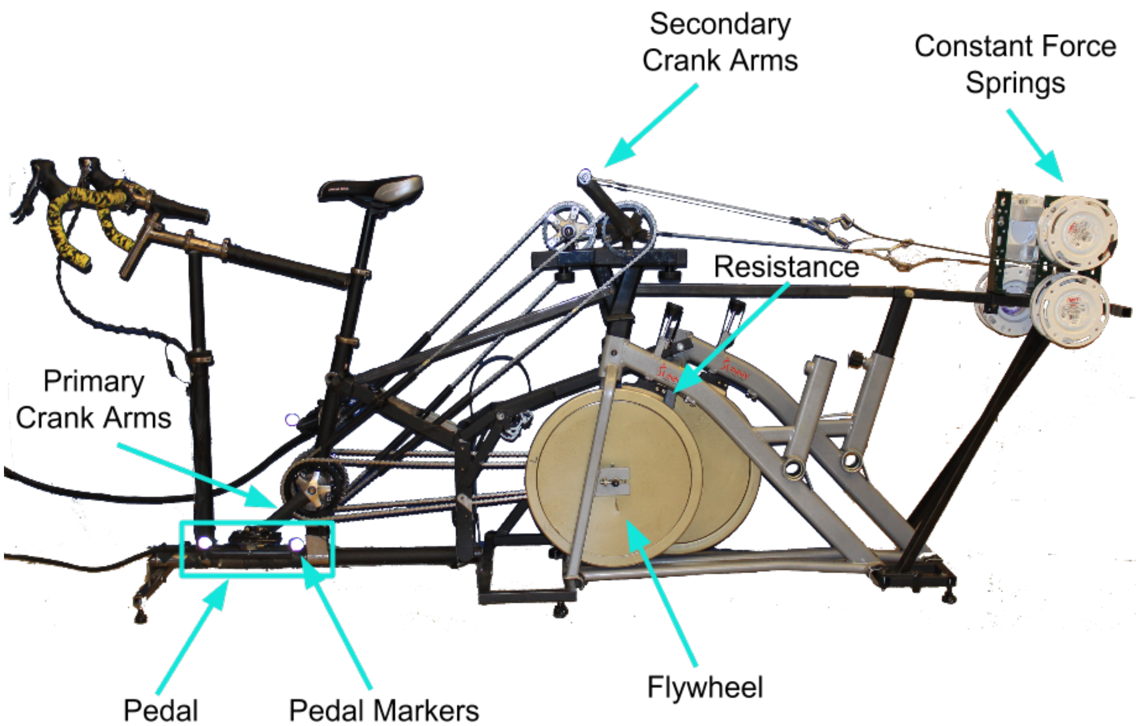

Figure 1: Split-crank cycling ergometer. The bracket connecting the cranks was cut and constant force springs were added to supply a resistive torque during extension and assistive torque during flexion. This ergometer simulates normal, coupled bilateral pedaling while providing a mechanical decoupling of the cranks.

phasing and cadence. Day 1 consisted of a training protocol in which subjects pedaled during 5x5-minute trials. Day 2 consisted of a single 5-minute trial.

2.3 KINEMATIC AND KINETIC RECORDING ANALYSES

During both days, kinematics and kinetics data were collected using a lower-body marker set and force transducers in the pedals. Markers were attached to each pedal to determine pedal and crank angles. Data were collected at 120 Hz using a 6-camera Vicon Motion Analysis system and analyzed via a custom Matlab code. All calculations were performed with respect to the dominant limb, which was considered to be the limb that produced the higher maximum crank torque.

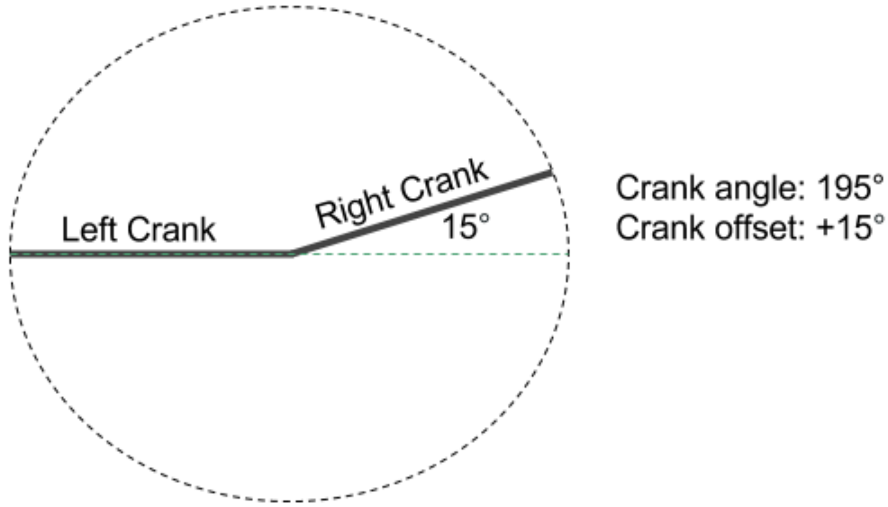

Figure 2: Crank offset measurement. Crank offset is defined as the deviation from perfect pedaling (180°). The angle between the cranks (crank angle) was measured with respect to the dominant side, and 180° was subtracted from this value to obtain crank offset. For example, in this figure, the crank angle was 195°. Once 180° was subtracted from 195°, the crank offset value of +15° was obtained.

2.3.1 Crank offset

Crank offset is defined as the deviation from perfect pedaling (Fig. 2). The angle between the left and right cranks was calculated with respect to the dominant side, and the deviation from 180° was recorded as the crank offset.

2.4 STATISTICAL ANALYSIS

Data was analyzed using a paired t-test. P-values of less than 0.05 were considered significant.

2.4.1 Adaptation

2.4.1.1 Crank offset within trials

To determine if the crank offset within trials changed significantly, a paired t-test was used. To determine if adaptation was occurring within trials, the difference in crank offset from minute 1 to minute 5 for each subject was calculated and a t-test was used to determine if these differences were significant in all trials. In addition, the differences in crank offset from minute 1 to minute 3 and minute 3 and minute 5 for each subject were calculated and tested for significance. This analysis was used to determine when subjects reach a baseline error within trials.

2.4.1.2 Crank offset across trials

To determine if crank offset changed significantly across trials, a paired t-test was used. First, the overall change in crank offset was tested for significance. The differences between trial 1 minute 1 and trial 5 minute 5 on day 1 were calculated for each subject. These differences were then tested for significance using a t-test. To determine when subjects reach a baseline error across trials, all 3 minutes were compared in succeeding trials. The difference between trial 1 minute 1 and trial 2 minute 1 for each subject was calculated and tested for significance. This was repeated for trial 2 minute 1 and trial 3 minute 1, trial 3 minute 1 and trial 4 minute 1, and trial 4 minute 1 and trial 5 minute 1. The same analysis was performed for minutes 3 and 5.

2.4.1.3 Ankle angle

To determine if there was a significant change in ankle angles, the average maximum and minimum ankle angles within and across trials were compared. To determine if ankle angle changed within trials, the differences between average maximum and minimum angles during minute 1 and minute 5 were computed for all trials. These differences were tested for significance using a t-test. To determine if ankle angle changed across trials, the differences between average maximum and minimum ankle angles during minute 3 were compared using a t-test. This comparison was made between trials 1 and 2, 2 and 3, 3 and 4, and 4 and 5.

2.4.1.4 Resultant force

The changes in resultant forces within and across trials were tested for significance using a paired t-test. To determine if resultant forces changed within trials, the difference between the average resultant forces in minute 1 and minute 5 was computed for each subject in all trials. These differences were then tested for significance. To determine if resultant forces changed across trials, the differences between average resultant forces during minute 3 were compared using a t-test. This comparison was made between trials 1 and 2, 2 and 3, 3 and 4, and 4 and 5.

2.4.1.5 Power Output

The changes in power output within and across trials were tested for significance using a paired t-test. To determine if power output changed within trials, the difference between the average power output in minute 1 and minute 5 was computed for each subject in all trials. These differences were then tested for significance. To determine if power output changed across trials, the differences between average power outputs during minute 3 were compared using a t-test. This comparison was made between trials 1 and 2, 2 and 3, 3 and 4, and 4 and 5.

2.4.2 Consolidation

To determine if consolidation occurred, the difference between minute 1 of day 1 trial 1 and day 2 were analyzed. The differences between minute 1 crank offset during day 1 trial 1 and day 2 were calculated for each subject. These differences were then tested for significance via a t-test.

2.4.3 Savings

To determine if savings occurred, the rates of improvement on day 1 trial 1 and day 2 were compared. The difference between day 1 trial 1 minute 1 and minute 5 was computed for each subject. The difference between day 2 minute 1 and minute 5 was also computed for each subject. These differences were then tested for significance using a t-test.

CHAPTER 3

RESULTS

3.1 ADAPTATION

3.1.1 Crank offset

3.1.1.1 Crank offset within trials

Subjects were able to decrease their crank offset within trials on days 1 and 2. On day 1, subjects decreased their crank offset between minutes 1 and 5 by 18.31% (4.44°), 10.30% (1.78°), 20.16% (3.75°), and 28.95% (5.81°) during trials 1, 3, 4, and 5 respectively (Fig. 3). During trial 2, all but 2 subjects showed an increase in crank offset between minutes 1 and 5. On average, crank offset increased by 12.20% (2.10°) during this trial. On day 2, subjects decreased their crank offset by 25.73% (4.58°), as can be seen in Fig. 4. All changes in crank offset between minutes 1 and minutes 5 on day 1 and day 2 were not significant. In addition, the change in crank offset followed a similar trend within trials. With the exception of trial 2, subjects exhibited the highest crank offset during minute 1 and their crank offset leveled out to a baseline value by minute 3. There were no significant differences between the crank offsets in minutes 3 and 5 on day 1 and day 2, with the exception of trial 3.

3.1.1.2 Crank offset across trials

Subjects were also able to decrease their crank offset across trials on day 1 (Fig. 3). Subjects significantly decreased their crank offset by 41.27% (10.02°) from the first

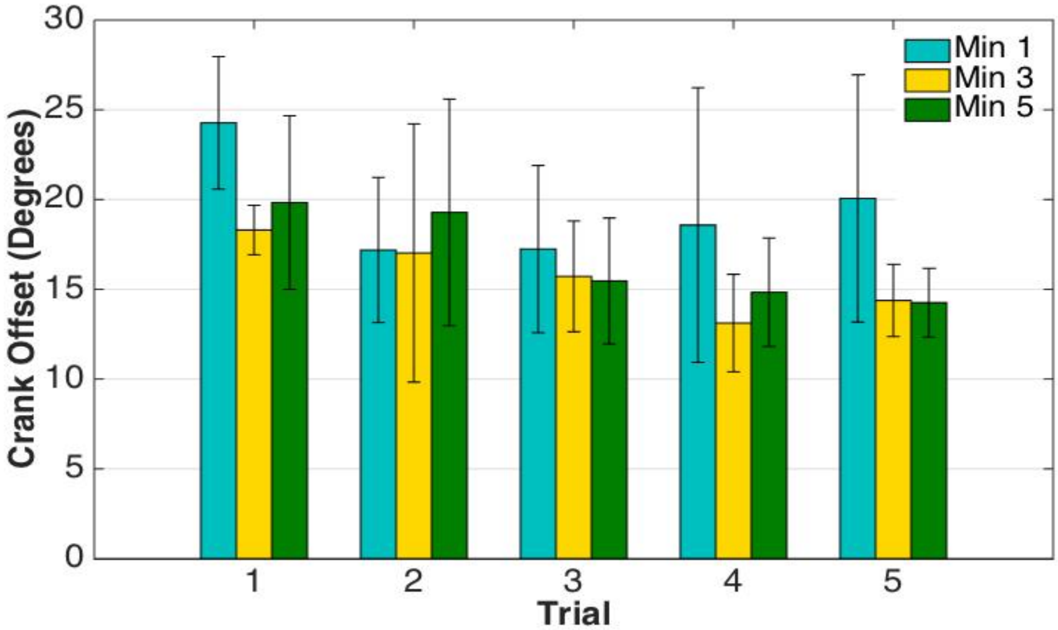

Figure 3: Average absolute crank offset on day 1. Crank offset decreased within and across trials. On day 1, subjects decreased their crank offset within trials by 18.31% (4.44°), 10.30% (1.78°), 20.16% (3.75°), and 28.95% (5.81°) during trials 1, 3, 4, and 5 respectively. On average, crank offset increased by 12.20% (2.10°) during trial 2. Subjects had the highest crank offset during minute 1 and reached a baseline crank offset by minute 3 within each trial. There were no significant differences between crank offsets during minutes 3 and 5, with the exception of trial 3. Crank offset significantly decreased by 41.27% (10.02°) during day 1. Subjects decreased their crank offset by 17.34% (4.21°), 21.43% (3.92°), and 28.12% (5.58°) during minutes 1, 3, and 5 respectively between trial 1 and trial 5. The improvement in crank offset during minute 3 was significant. Crank offsets significantly decreased between trials 1 and 2. Succeeding trials showed a decrease in crank offset, but these differences were not significant.

minute of trial 1 to the last minute of trial 5. When comparing the improvement during each minute of cycling, it was found that subjects decreased their crank offset by 17.34% (4.21°), 21.43% (3.92°), and 28.12% (5.58°) during minutes 1, 3, and 5 respectively between trial 1 and trial 5. The improvement in crank offset during minute 3 was significant.

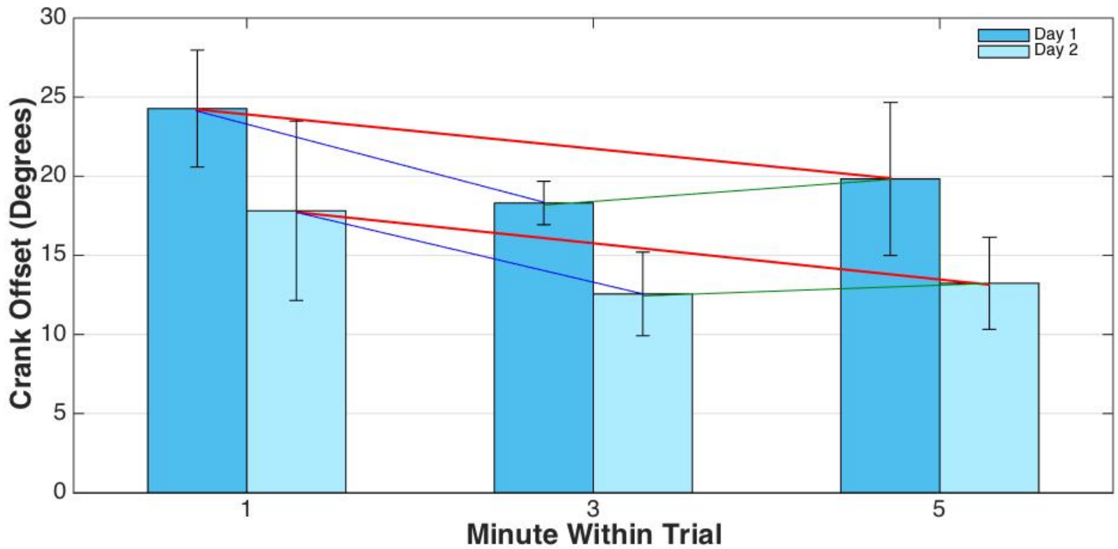

Figure 4: Average absolute crank offset during first 5 minutes of cycling on day 1 and day 2. Subjects were able to peddle with a lower crank offset during the first 5 minutes of cycling on day 2. They decreased their crank offset by 25.73% (4.58°) on day 2. On day 2, subjects reached a baseline crank offset by minute 3. The crank offset on day 2 was 26.61% (6.46°) lower than on day 1 during minute 1, 31.39% (5.75°) lower during minute 3, and 33.28% (6.60°) lower during minute 5. These differences were not significant. There were no significant differences in the rates of improvement on day 1 and day 2.

Crank offset significantly decreased during minute 1 between trials 1 and 2. After this initial improvement, crank offset increased during minute 1 between remaining trials; however, these increases in crank offset are not significant. During minute 3, crank offset decreased with each succeeding trial, with the exception of trial 5 where it increased. Though there is an improvement in crank offset during this minute, none of the differences are significant. Crank offset during minute 5 decreased between each trial. Only the difference between trial 1 and trial 2 minute 5 crank offsets was significant.

When comparing the crank offsets on day 2 and the last 5 minutes of cycling on day 1 (trial 5), it was found that the crank offsets were very similar. On day 1, subjects were able to reach a crank offset of less than 15° degrees after 25 minutes of cycling. On day

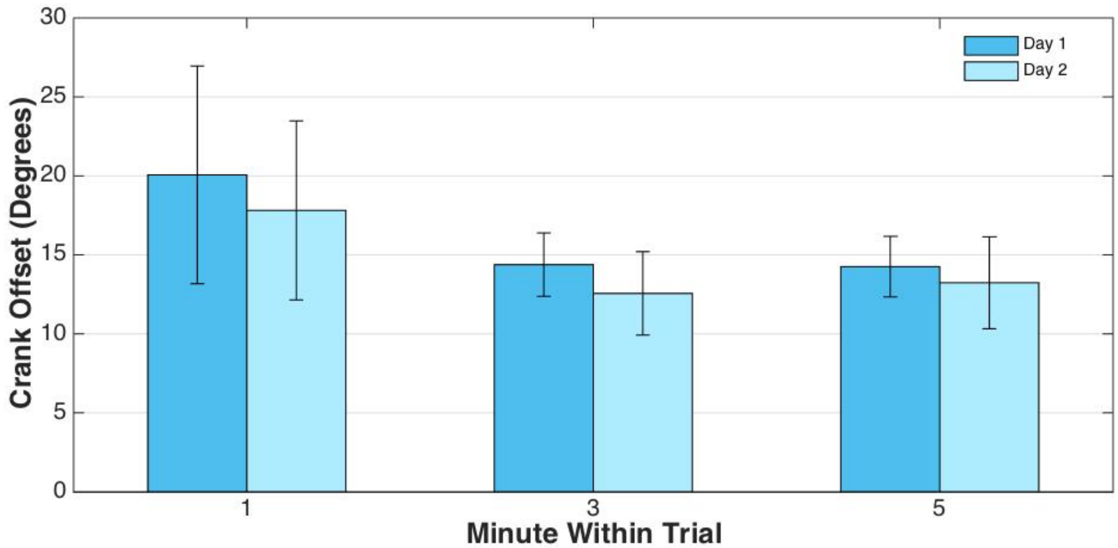

Figure 5: Average absolute crank offset during last 5 minutes of cycling on day 1 and first 5 minutes of cycling on day 2. Crank offsets during the first 5 minutes of cycling on day 2 were similar to the crank offsets during the last 5 minutes of cycling on day 1 (trial 5). On day 1, subjects were able to reach a crank offset of less than 15° degrees after 25 minutes of cycling. On day 2, subjects were able to reach a crank offset of less than 14° after just 5 minutes of cycling. There were no significant differences between data collected at each minute during these 2 trials.

2, subjects were able to reach a crank offset of less than 14° after just 5 minutes of cycling. There were no significant differences between crank offsets at the end of day 1 and at the beginning of day 2 (Fig. 5).

3.1.2 Ankle angles

During day 1, subjects maintain a fairly constant ankle angle throughout each cycle (Fig. 6). There were no significant differences in the maximum and minimum ankle angles within or across trials.

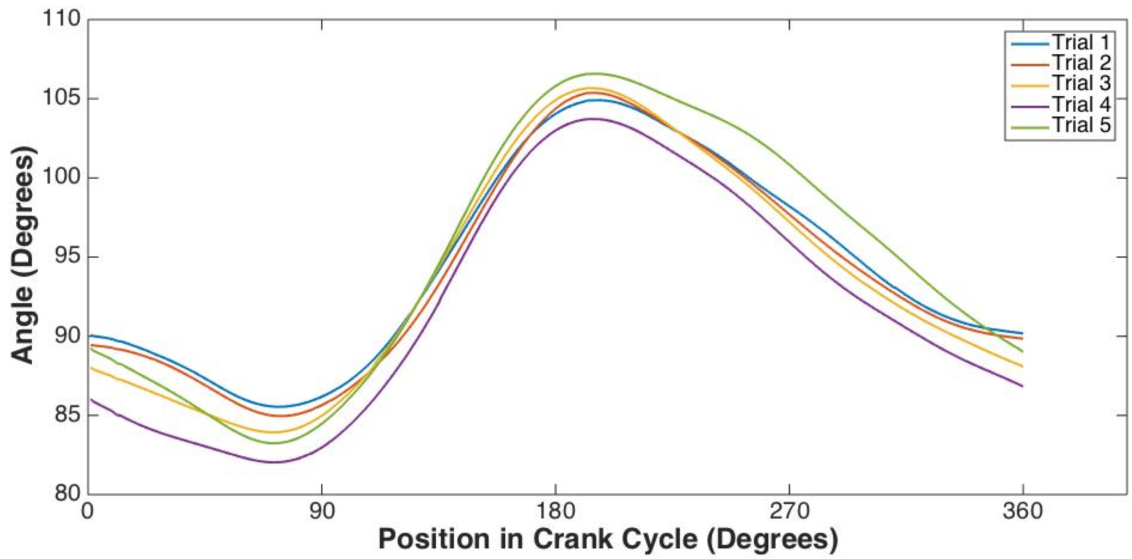

Figure 6: Average ankle angles during minute 3 of all day 1 trials. On day 1, subjects did not change their ankle angle significantly, though the maximum angle increased and the minimum angle decreased with each successive trial.

3.1.3 Resultant forces

Resultant forces significantly changed on day 1 (Fig. 7). Though there was no visible trend across trials, such as steadily increasing or decreasing resultant forces, resultant forces changed significantly across trials. In addition to varying across trials, resultant forces varied significantly within trials, with the exception of trial 3. There was an increase in forces during trials 1-4 and a decrease during trial 5.

3.1.4 Power Output

Power output did not change significantly within or across trials on day 1 (Fig. 8).

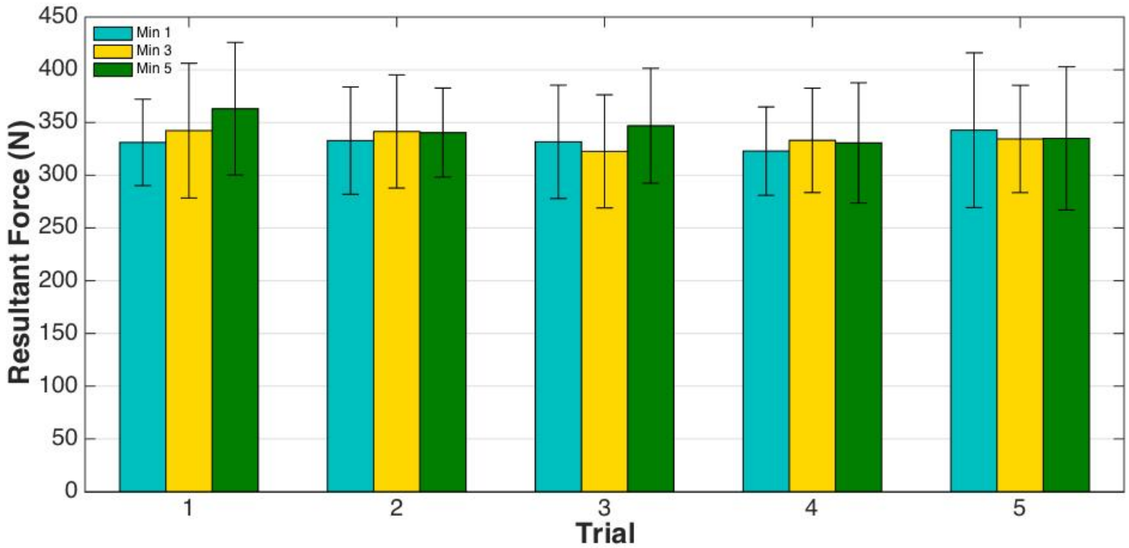

Figure 7: Average day 1 resultant forces varied significantly. There was no visible trend in varying resultant forces across trials; however, changes in resultant forces across trials were significant. Resultant forces changed within all trials, with the exception of trial 3.

3.2 CONSOLIDATION AND SAVINGS

On day 2, subjects were able to cycle with a lower crank offset during minute 1 than during the corresponding minute on day 1 (Fig. 4). The crank offset on day 2 was 26.61% (6.46°) lower than on day 1 during minute 1; however, this difference was not significant. In addition, though subjects were able to decrease their crank offset on both days 1 and 2, there was no significant difference in the rate of improvement.

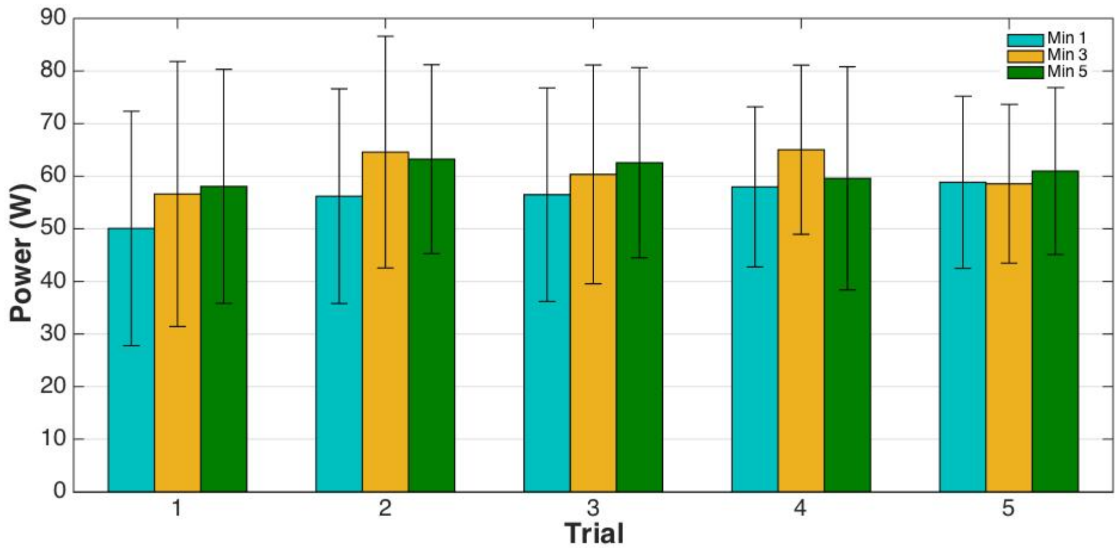

Figure 8: Average day 1 power output did not vary significantly. There were no significant changes in power output within or across trials on day 1.

CHAPTER 4

DISCUSSION AND CONCLUSION

4.1 DISCUSSION

4.1.1 Adaptation

Results show that subjects were able to reach their baseline crank offset, an average of 17.03°, after just 2 trials. In addition, subjects were able to reach a baseline within trials by the third minute of cycling. This suggests that subjects only need about 10 minutes of training to reach the same baseline crank offset they maintain after 25 minutes of cycling. Subjects were able to adapt to the ergometer and decrease their crank offset within and across trials (Fig. 3). The results suggest that most of the adaptation occurred in the first minute of cycling. By the time subjects were in their third minute of cycling, their rate of improvement in crank offset slowed and subjects reached a baseline crank offset of less than 20°. On day 1, crank offset decreased by 41.27% (10.02°) from the first minute of pedaling in trial 1 to the last minute of pedaling in trial 5. Though subjects continued to improve their crank offset across trials, results suggest that most of the adaptation occurs during the first two trials, as only the improvement in crank offsets between trials 1 and 2 is significant.

4.1.2 Time course

Since savings is characterized by a faster rate of relearning, the rate of improvement in crank offset on day 1 within trial 1 was compared to the rate within the trial on day 2. There was no significant difference in the rate of improvement between the first 5 minutes of cycling on day 1 and on day 2. This shows that, though there was ultimately an improvement in crank offset, savings did not occur.

To determine if consolidation occurred, crank offsets during each minute on day 1 trial 1 and day 2 were compared. Crank offsets on day 2 were lower than on day 1, but the differences were not significant. This suggests that, even though improvement was seen, consolidation did not occur. However, subjects were able to cycle the ergometer on day 2 with the same crank offset as the last 5 minutes of cycling on day 1. Since there was no significant difference between crank offsets in day 1 trial 5 and day 2, results showed that subjects could retain their improvement on a subsequent day.

4.1.3 Mechanism of adaptation

Kinetics and kinematics data were gathered to determine the mechanisms of adaptation to the split-crank ergometer. There were no significant changes in ankle angle or power output as subjects were adapting, suggesting that overall biomechanical performance was always achieved. Subjects did, however, significantly vary their resultant forces within and across trials, which means that effective crank force was maintained even though resultant forces changed. This leads to the conclusion that subjects may have modulated their resultant forces independently of effective crank force as they adapted to the split-crank ergometer to decrease crank offset.

4.2 CONCLUSION

Subjects were able to adapt to the split-crank ergometer and decrease their crank offset within and across trials. After 25 minutes of cycling on day 1, subjects were able to cycle with an average crank offset of less than 15°. Subjects began to reach a baseline crank offset by trial 2, and within each trial subjects reached a baseline crank offset by minute 3. On a subsequent day, subjects were able to cycle with a crank offset of less than 14° after just 5 minutes of cycling. Subjects were able to cycle with a crank offset on day 2 that was not significantly different from their crank offset during the last 5 minutes of cycling on day 1. Though subjects started cycling at a lower crank offset during the first minute of cycling on day 2 when compared to the first minute on day 1, the improvement was not; therefore, subjects did not exhibit consolidation or savings. These results suggest that subjects can reach a baseline crank offset of less than 20° after just 10 minutes of cycling on day 1 and can reach this same baseline crank offset after 3 minutes of cycling on a subsequent day. Resultant forces changed significantly within and across trials as subjects adapted to the ergometer, suggesting that subjects may vary their force output as a method of adaptation.

CHAPTER 5

FUTURE WORK AND ACKNOWLEDGEMENTS

5.1 FUTURE WORK

Future work should focus more on the mechanism of adaptation as well as consist of a longer time period of cycling. It would be beneficial to have subjects cycle on day 2 for the same time period that they cycled on day 1. This would allow for a better determination of whether or not consolidation and savings occur. Having subjects cycle for more than 25 minutes may reveal a lower baseline crank offset than what was achieved in this study. In addition, more research should be done on determining the mechanisms of adaptation. Results showed that overall biomechanical performance was always achieved and that resultant forces may be modulated independently of effective crank force to decrease crank offset. Research should focus on whether or not this is true as well as perform a closer look into other kinetic and kinematic changes that may be occurring. Once this has been determined, future work can study whether pathologic populations will be able to demonstrate similar adaptation to the split-crank ergometer, as has been shown here in an able-bodied population.

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